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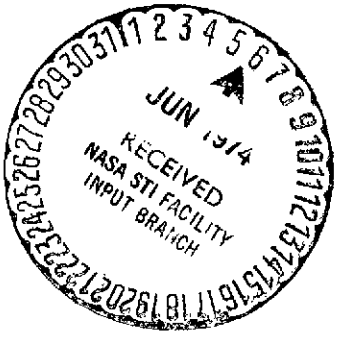

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16. Abstract

An engineering method of determining nonstationary temperature fields in the cross sections of such profiles as turbine blades under conditions of thermal fatigue is proposed. The method is based on the precise determination of the surface temperature by means of thin-film thermocouples which are characterized by a negligible rise time and which do not distort the temperature field of a sample or the aerodynamics of the flow about it.

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TEMPERATURE FIELDS IN PROFILE SAMPLES DURING THERMAL FATIGUE TESTING

D.F. Simbirskiy, A.V. Oleynik, and A.Ya. Anikin

The purpose of thermal fatigue tests on refractory materials /16* for gas turbine engine blades is to obtain the dependence of the number of cycles to fracture of special profile samples on the magnitude of the thermal stresses or deformations. The profile samples, the models of the blades are subjected to heating up to 700-1100°C temperatures in a medium of kerosene combustion pro- /17 ducts and are then cooled in an airstream up to 200-300°C. The heating-cooling cycle is repeated until thermal fatigue failure traces appear on the samples. The thermal stresses or deformations in the sample at such a temperature level can only be estimated at the present time by determining the temperature fields inside the sample. This requires that the boundary conditions on its surface be given. The boundary conditions of the third kind that are usually used, the temperature of the flow and the distribution of the heat transfer coefficients on the surface of the part, are determined for blade profiles with errors which are as large as 20-50% in some cases [1]. During thermal fatigue tests of profile samples which are made on ordinary burners without a careful preparation of the aerodynamics of the flow around the sample, it is not possible at all to give the boundary conditions with the admissible accuracy.

Below we discuss a method for determining the temperature fields from the boundary conditions of the first kind, the temperatures on the surface of the samples at each instant obtained with the aid of film-thermocouples on the surface. The measurement of the surface temperatures by the usual wire thermocouples leads to a disturbance in the geometry and heat-exchange conditions of the sample with the gas flow, and as a result a distortion of the

*Numbers in the margin indicate pagination in the foreign text.

temperature field.

The possibility of using film-thermocouples to measure the temperature fields of parts made from refractory nickel-chromium alloys in the temperature range up to 1000°C was investigated. The insulator films 2 consisting of narrow and thin strips from /18
the point where the temperature is measured to the place where the signal from the thermocouple is picked up are applied to the surface of the part 1 (Fig. 1). Next the metallic film thermoelectrodes 4 are deposited on the film. The thermocouple junction 3 is formed at the place where the film thermoelectrodes and the metal of the part make contact (meet). The thermoelectromotive force is picked up from the thermocouple using the current pickup 5 and the material of the part serves as the second thermoelectrode.

The measurement scheme presented in Fig. 2c is intended for the general case when it is not possible to select wires which are thermoelectrically identical to the film thermoelectrode and the material of the part. A couple of wire thermoelectrodes C and D whose characteristic $E_{C0}(t_0, 0)$ is close to the characteristic $E_{AB}(t_0, 0)$ of the film thermocouple A (film thermoelectrode) and B (material of the part) are selected. t_0 is the temperature in the region where the wire electrodes are connected to the film electrodes. The ends of the thermoelectrodes C and D are thermostatically controlled at the temperature $t = 0$ and copper wires leading out to the measurement instrument are connected to them. When the junction is thermostatically controlled at the temperature t,

$$\left.\begin{aligned} E_{AB}(t, 0) &= E + \Delta(t_0, 0); \\ \Delta(t_0, 0) &= E_{AB}(t_0, 0) - E_{CD}(t_0, 0), \end{aligned}\right| \qquad (1)$$

where E is the magnitude of the electromotive force measured by the potentiometer.

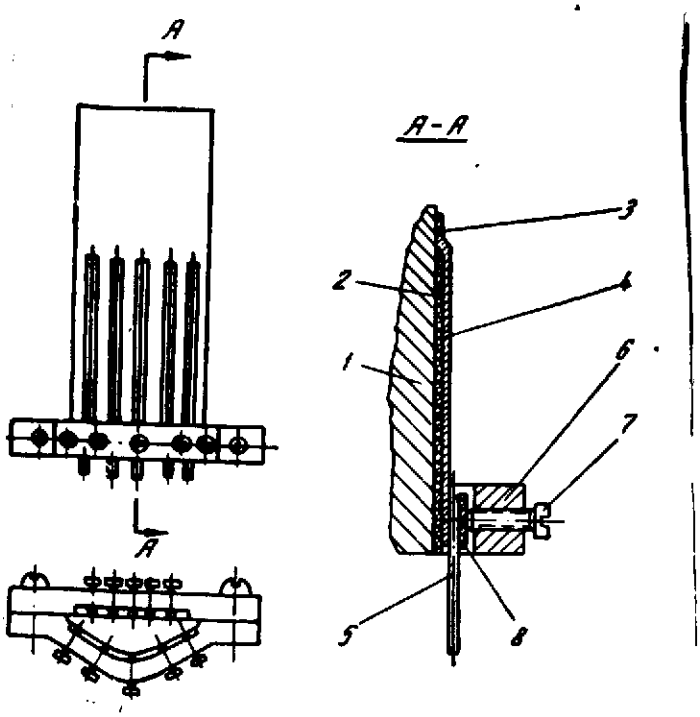

Fig. 1. Design and schematic diagram for the preparation of a sample for thermal fatigue tests using film surface thermocouples:
1 - profile sample; 2 - insulator-backing for film thermocouple; 3 - thermocouple junction; 4 - take off film; 5 - wire lead; 6 - metallic body of current pickup; 7 - clamping screw; 8 - mica insulator backing

The material selected for the film electrode was nickel, which has a number of advantages, namely: moderate oxidation at temperatures up to 900-1000°C, stability in various chemically active media and in addition nickel is one of the most convenient metals to apply. When it reaches the temperatures at which active oxidation in /19
air begins (700-800°C), and after prolonged soaking at 1000°C wire nickel preserves its thermoelectrical properties, since the oxide film which appears on the surface protects the interior layers from oxidation. The thermoelectric stability of nickel at temperatures up to 1000°C depends to a high degree on its chemical purity and it is good for nickel whose purity approaches 99.95% [3].

The nickel film was obtained by the vacuum-spray coating method. An alundum crucible was used as the vaporizer. A separate heater was used to heat the backing before it was spray-coated to maintain the required temperature during the spray-coating and the subsequent thermal treatment of the films.

The physical characteristics of the film depend to a considerable degree on the roughness of the backing surface, the nickel

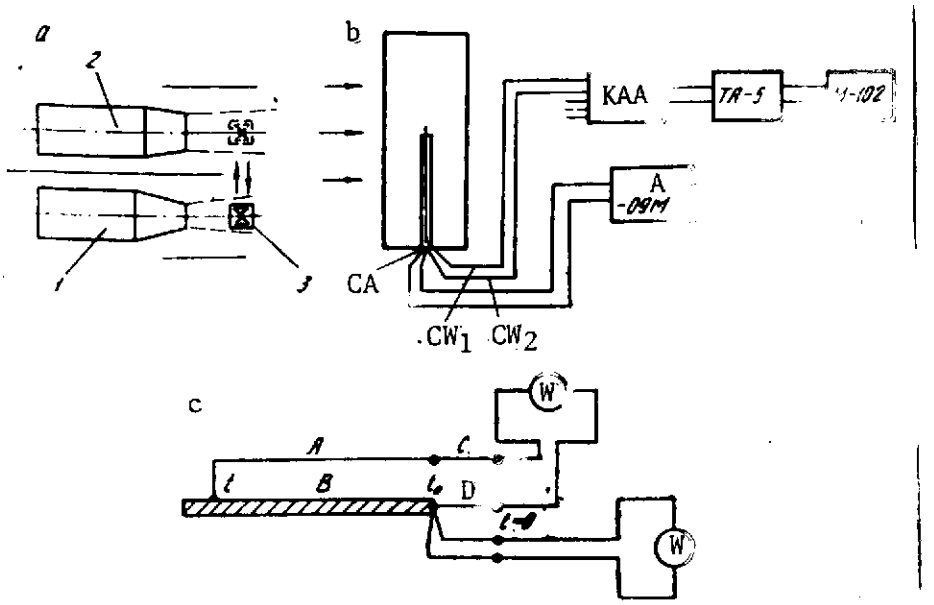

Fig. 2. Schematic diagram for thermal fatigue tests with kerosene-burner heating. (a) Block-diagram of measurement channel; (b) and recording of signals from film thermocouple; (c):

1 - burner; 2 - cooler (air); 3 - cassette with samples; CA - thermocouple junction for determining parting temperature; CW_1 - compensating wire "-"; CW_2 - compensating wire "+"; KAA - keyed amplifier attachment; TA-5 extensometer amplifier; H-102 - loop oscillograph

Key: A. RP [recording potentiometer]

vaporization regime, the temperature of the backing and the thermal treatment regime of the film after its condensation. When the insulator-backing was selected, preference was given to refractory enamels, which as a result of their small porosity have better corrosion-resistant and electroinsulating properties. The thicknesses of the film thermoelectrodes that were studied varied in the range from 0.5 to 40 μm (spray-coating time up to 1 hour). The quality of the film thermoelectrode (resistance to oxidation and stability of the main characteristic), all other conditions being equal, depends on its thermal treatment in vacuum immediately after the spray-coating. Thus for a nickel film which settled on the backing without subsequent thermal treatment, the resistance sharply increases at 550-600°C temperatures in air. This indicates the beginning active oxidation of the surface layers of the film,

which is approximately 200°C lower than in solid nickel.

Nickel films that were subjected to thermal treatment in vacuum after the spray coating turned out to be much more stable and heat-resistant. When held in vacuum for 1 hour at temperatures above 400-450°C the film thermoelectrodes showed greatest hardness and mechanical strength. The beginning oxidation was characterized by 750-800°C temperatures and the film thermoelectrodes operated at a 1000°C temperature not less than 1.5 hours, preserving a constant characteristic until breakdown.

To investigate the film thermocouples sample-plates made from thermometer and special refractory alloys (chromel, alumel, EI-435, EP-109, ZhS6-K, and other materials) were prepared.

The stability and reproducibility of the thermocouple readings were studied by constructing and subsequently comparing the main calibration characteristics obtained from repeated heatings up to 500, 600, ..., 1000°C temperatures, holding them 15 min at these temperatures. The concluding stage of the tests was heating the film up to 1000°C and holding it at this temperature until complete oxidation, with continuous measurement of the thermoelectromotive force.

The resistance of the film thermoelectrode to high temperature oxidation was studied by plotting the relation between the resistance of the film and junction and the temperature during continuous heating in air up to a temperature of 1000°C. Step annealing in air was also used, with a 15 min holding time at 500, 600, 700, 800, 900 and 1000°C temperatures with subsequent cooling and measurement of the resistance of the film and junction.

As an example we give the data for a nickel-ZhS6-K couple, /20 whose instability according to the data from 12 heatings is characterized by a root mean square deviation equal to ±2°C in the range up to 600°C and ±7°C in the range up to 1000°C. The service life of this thermocouple at 1000°C is at least 1.5 hours. The total thickness of the thermocouple (insulator plus film thermoelectrode) is not greater than 0.05 mm. The magnitude of the thermoelectromotive force is approximately 30 μV per degree.

Thus the studies that were made confirm that it was possible to use surface film thermocouples in the thermal fatigue testing of profile samples.

Figure 1 gives the outer shape of the profile sample, the schematic diagram for its preparation using ten surface film thermocouples and the design of the mechanical current pickup. The plane (two-dimensional) problem was studied: the temperature fields were in the middle cross section along the contour of which the temperature measurements were made. The schematic diagram for carrying out the thermal fatigue tests of the profile samples with kerosene-burner heating and cooling by an airstream is given in Fig. 2a.

Two samples secured in the cassette were gradually displaced with the aid of an electromagnet from the kerosene combustion product flux whose temperature was 1400-1600°C into the cooling airstream whose temperature was 20°C. Figure 2b shows the block diagram of the measurement channel. The signals from the 8-10 film thermocouples were transferred to the loop of the magnetoelectric oscillograph with the aid of the key-amplifier device operating with the extensometer amplifier. The temperature at the spot where the wire leads were connected to the film thermoelectrodes was determined from the readings of the usual chromel-

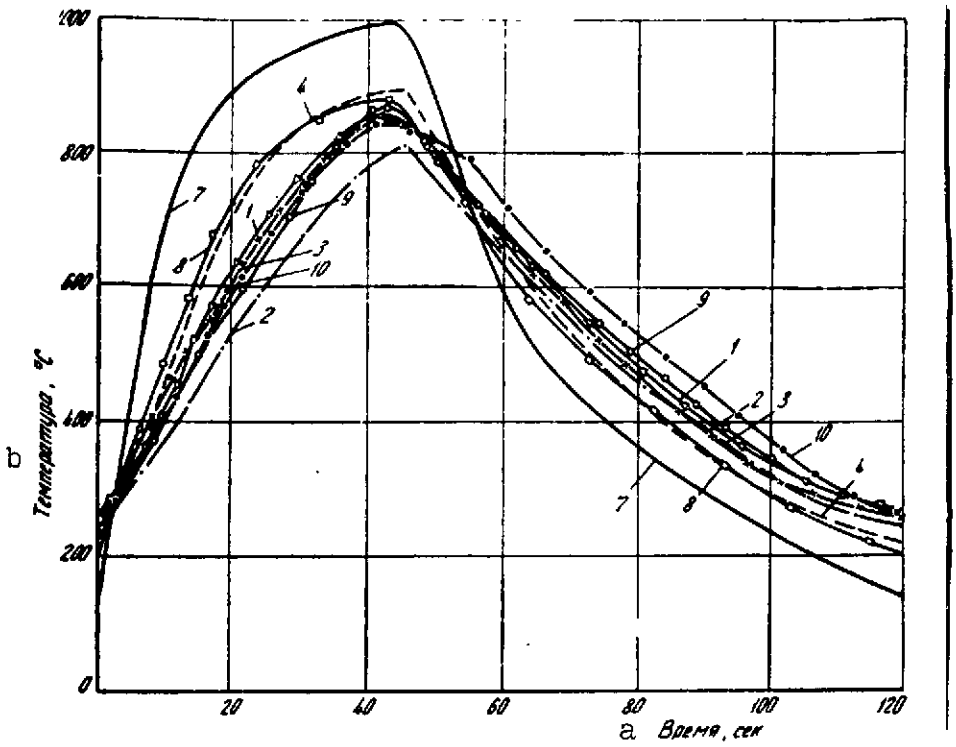

Fig. 3. Variations in the temperature at points of the cross section of a profile sample obtained from surface film thermocouples during thermal cycles.

Key: a. Time, sec
b. Temperature

alumel thermocouples that were recorded on an RP-09M recording potentiometer. A sample of the decoded oscillogram is given in Fig. 3. The heating and cooling half-cycle time was 40-50 sec. /21

The temperature fields were determined either by calculations on an electronic digital computer or from a combined model using the electrical heat analogy, consisting of electroconductive paper and the resistances [2]. In both cases the Liebman scheme was used with a nonuniform breakup of the profile sample into blocks.

The heat balance equation for block "0" (Fig. 4) is expressed as follows:

$$\frac{c_0\gamma_0\Delta S_0}{\Delta\tau}(T_{0,n}-T_{0,n-1})=\sum_{i=1}^{k}\frac{\lambda_{0-i}(T_{i,n}-T_{0,n})}{\Delta l_{0-i}}\Delta h_{0-i}, \qquad (2)$$

where $T_{0,n}$ and $T_{i,n}$ are the temperatures of the zero-th and i-th blocks at the instant n; $T_{0,n-1}$ is the temperature of the zero-th block at the instant n - 1; $\Delta\tau$ is the time interval; c_0 and γ_0 are the specific heat and density of the material of the sample; ΔS_0 is the area of the block; Δl_{0-i} and Δh_{0-i} is the distance between the centers and the width of the boundary of the blocks 0 - i; λ_{0-i} is the heat conductivity coefficient on the 0 - i sector; k is the number of neighboring blocks; $\left|\frac{\Delta l_{0-i}}{\lambda_{0-i}\Delta h_{0-i}}\right|$ is the thermal resistance of the sector.

For an interior block bordering only interior blocks, Eq. (2) can be written as:

$$A_0 T_{0,n} + \sum_{i=1}^{k} B_{0-i}(T_{0n} - T_{i,n}) = A_0 T_{0n-1}, \qquad (3)$$

where $A_0 = \frac{c_0\gamma_0\Delta S_0}{\Delta\tau}$ is the coefficient of the "0" block;

$B_{0-i} = \frac{\Delta h_{0-i}}{\Delta l_{0-i}}\lambda_{0-i}$ is the interblock coefficient.

The quantity $c_0\gamma_0$ refers to the temperature $T_{0,n-1}$, the quantity λ_{0-i} to the temperature $\frac{T_{0,n-1} + T_{i,n-1}}{2}$. It is assumed that the right member of Eq. (3) is known.

When one block z out of k neighboring blocks is a boundary block, the equation takes on the form:

$$A_0 T_{0,n} + \sum_{i=1}^{k} B_{0-i} T_{0,n} - \sum_{i=1}^{k-1} B_{0-i} T_{i,n} = A_0 T_{0,n-1} - B_{0-z} T_{z,n}. \qquad (4)$$

In Eq. (4) the value of $T_{z,n}$ is given by the boundary conditions, the temperature on the contour at the point z at the n-th instant of time.

A system of linear algebraic equations is set up to find the $T_{i,n}$ (in the case under consideration, a 17-th order system) to /22 calculate the nonstationary temperature fields on an electronic digital computer from Eqs. (3) and (4). This system can be solved on an electronic digital computer, and its solution is the basis for the next time step. The calculation of one heating-cooling cycle with 50-60 time steps on the "Minsk-22" computer takes about 20 minutes. In the general case the position of the points 21-32 along the contour of the model may differ from the points at which the temperatures are measured by the film thermocouples. Therefore, in the beginning it is necessary to approximate the temperature distribution curves along the contour involute of the sample cross section. A parabola along each of the three sides of the sample was used for the approximation.

Determination of the Temperature Fields on the Model

The equation of the Kirchhoff law for the electrical model of a block around the point 0 is expressed as follows [1]:

$$\frac{V_{0,n}-V_{0,n-1}}{R\tau}=\sum_{i=1}^{k}\frac{V_{i,n}-V_{0,n}}{R_{0-i}} \qquad (5)$$

By analogy with Eqs. (2) and (5), we obtain the following expressions for the elements of the grid which realize the Liebman scheme:

$$R_{0-i}=\frac{1}{B_{0-i}}R_N;$$

$$R_{\tau_0}=\frac{1}{A_0}R_N.$$

When the resistances R_{0-i} are replaced by electroconductive paper (the case of a combined R-grid-electroconductive paper model [2] the transformation scale is $R_N = R_{\square}\lambda_{0-i}$, where $R_{\square}$ is the resistance of a square of paper.

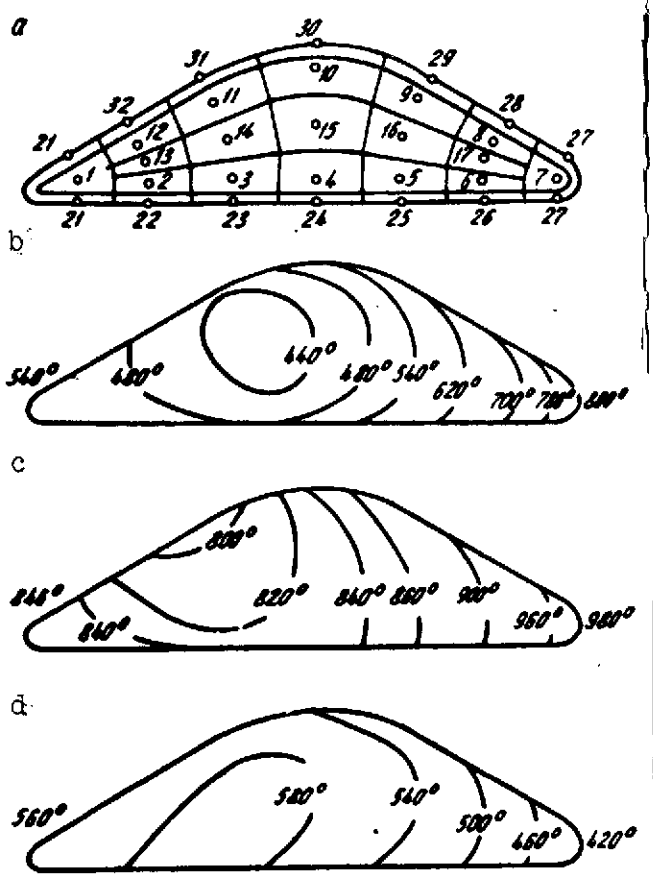

Fig. 4. Partition scheme for cross section of sample (a) and isotherms for selected time instants during the thermal cycles (Fig. 3):

τ = 17 sec (b), τ = 40 sec (c), and τ = 73 sec (d)

Consequently, for the ultimate resistance at the node 0, we can write:

$$R_{\tau_0} = \frac{a_0 \Delta\tau}{\Delta^2_0} R_{\square}, \qquad (6)$$

where $a_0 = \lambda_0/c_0\gamma_0$ is the temperature conductivity coefficient referred to the temperature $T_{0,n-1}$ at the point 0. /23

The model was cut out from electroconductive paper with $R_{\square}$ = 4.2 kohm, according to the geometry and dimensions of the cross section of the profile sample given in Fig. 1 in the scale 50:1. The grid has a variable step which is smaller in the region of the front and rear edges of the sample where the maximum temperature gradients are expected. At the points 21 to 32 on the contour of the model, boundary conditions of the first type are realized, i.e. the surface temperatures determined with the aid of the film thermocouples are given. The resistances R_τ were collected on the EMSS-7M integrator grid.

The corresponding EGDA-9/60 integrator blocks were used for the specification and measurement of the potentials.

The solution is obtained as follows. At the instant "n" voltages corresponding to the boundary conditions at these points at the n-th instant of time are supplied from the potentiometer voltage divider to the points 21, 22, ... on the boundary of the model. The potentials corresponding to the temperatures at the interior points at the (n-1)-th instant of time are supplied to the resistor input R_T. The voltages at the internal nodes of the model corresponding to the temperatures at these points at the n-th instant of time are measured by the measurement device. The computation for the (n+1)-th instant is analogous, etc.

Any temperature distribution can be selected for the initial conditions inside the body. The error resulting from the arbitrariness of the initial distribution vanishes after 8-10 solution steps. Since the cycle is repeated periodically, the temperature distribution obtained at the end of the first cycle is taken as the initial distribution for the next cycle. The computations are repeated until the solutions obtained in the given cycle no longer coincide with the solutions obtained in the previous cycle. The number of computational steps for the convergence of the distribution to the true temperature distribution with arbitrarily given initial conditions was determined experimentally. This number does not exceed 10-15% of the total cycle time.

The nonstationary temperature fields during thermal fatigue tests in a ZhS6-K alloy profile sample cross section have been determined. The maximum cycle temperature was 900°C and the minimum temperature was 200°C. The results of the temperature measurements along the cross section of a sample of average height obtained by the surface film thermocouples given in Fig. 3 were used for specifying the boundary conditions.

The values of the heat conductivity coefficient λ, the heat coefficient C and the density γ enter the ultimate resistance R_T as the temperature conductivity coefficient a. The resistances were varied every 200° during the solution. Check calculations have shown that in the given example it suffices to take into account the thermo-physical properties in this manner. The selection of the time step $\Delta\tau$, which determines the amount of work, is of considerable importance. It is known that the increase in the accuracy of the solution is proportional to the square of the decrease in the time step [1]. But decreasing the step by one half doubles the number of computations and increases the computing time. To select the optimal step, the solution was obtained using various step sizes. It turned out that the solution obtained with the step size $\Delta\tau$ = 2.56 sec differed from the solution with the step size $\Delta\tau$ = 1.28 sec by not more than 0.5-0.8%. Therefore /24 the step size $\Delta\tau$ = 2.56 sec was taken as the optimal step size.

As a result of the modeling discrete temperature values were obtained at points of the grid, which can be used to construct isotherms. Figure 4 gives the isothermal curves in the cross section of a profile sample for some characteristic points in the cycle.

A comparative analysis of the results obtained from calculating the cycles on an electronic digital computer with the data from the model showed that the temperature fields obtained by the two methods that were mentioned coincide with a scatter not exceeding 0.5-1%. The normalized value of the relative error in the first approximation characterizes the general accuracy of the solution.

Thus, engineering methods can be used to determine the non-stationary temperature fields in the cross section of a profile sample during thermal fatigue tests.

A specific feature of the solution is the use of boundary conditions of the first kind which are given with high accuracy (an error not exceeding 1-1.5%). When the electrical heat analogy was used, the combined model was calculated and set up, and recommendations were made for the selection of the time step and the initial conditions. A sufficiently simple algorithm was proposed for the electronic digital computer, for which the computing time used up to calculate one cycle on the "Minsk-22" computer is 15-20 minutes.

The boundary conditions of the first type, the temperatures on the surface, were determined with the aid of surface film thermocouples which do not introduce distortions into the temperature field of the sample and the aerodynamics of the flow around it and also have a negligibly small time lag.

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